REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
2011

2. REPORT TYPE
Journal Article-Eur Journal of Applied Physiology

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Thermal face protection delays Fnger cooling and improves thermal comfort during cold air exposure

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
C. O'Brien, J.W. Castellani, M. Sawka

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Thermal and Mountain Medicine Division
U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

8. PERFORMING ORGANIZATION REPORT NUMBER
M10-47

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Same as #7 above.

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
When people dress for cold weather, the face often remains exposed. Facial cooling can decrease finger blood flow, reducing finger temperature (Tf). This study examined whether thermal face protection limits Wnger cooling and thereby improves thermal comfort and manual dexterity during prolonged cold exposure. Tf was measured in ten volunteers dressed in cold-weather clothing as they stood for 60 min facing the wind (¡15°C, 3 m s¡1), once while wearing a balaclava and goggles (BAL), and once with the balaclava pulled down and without goggles (CON). Subjects removed mitts, wearing only thin gloves to perform Purdue Pegboard (PP) tests at 15 and 50 min, and Minnesota Rate of Manipulation (MRM) tests at 30 and 55 min. Subjects rated their thermal sensation and comfort just before the dexterity tests. Tf decreased ($p < 0.05$ for time £ trial interaction) by 15 min of cold exposure during CON (33.6 § 1.4–28.7 § 2.0°C), but not during BAL (33.2 § 1.4–30.6 § 3.2°C); and after 30 min Tf remained warmer during BAL (23.3 § 5.9°C) than CON (19.2 § 3.5); however, by 50 min, Tf was no difference between trials (14.1 § 2.7°C). Performance on PP fell ($p <$

15. SUBJECT TERMS
Reflex vasoconstriction, Heat loss, Thermal sensation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Catherine O'Brien
Unclassified	Unclassified	Unclassified	Unclassified	9	19b. TELEPHONE NUMBER *(Include area code)* 508-233-5973

Reset

Thermal face protection delays finger cooling and improves thermal comfort during cold air exposure

Catherine O'Brien, John W. Castellani & Michael N. Sawka

European Journal of Applied Physiology

ISSN 1439-6319
Volume 111
Number 12

Eur J Appl Physiol (2011) 111:3097-3105
DOI 10.1007/s00421-011-1931-2

Springer

Eur J Appl Physiol (2011) 111:3097–3105
DOI 10.1007/s00421-011-1931-2

ORIGINAL ARTICLE

Thermal face protection delays finger cooling and improves thermal comfort during cold air exposure

Catherine O'Brien · John W. Castellani · Michael N. Sawka

Received: 27 January 2011 / Accepted: 16 March 2011 / Published online: 3 April 2011

Abstract When people dress for cold weather, the face often remains exposed. Facial cooling can decrease finger blood flow, reducing finger temperature (T_f). This study examined whether thermal face protection limits finger cooling and thereby improves thermal comfort and manual dexterity during prolonged cold exposure. T_f was measured in ten volunteers dressed in cold-weather clothing as they stood for 60 min facing the wind (−15°C, 3 m s^{-1}), once while wearing a balaclava and goggles (BAL), and once with the balaclava pulled down and without goggles (CON). Subjects removed mitts, wearing only thin gloves to perform Purdue Pegboard (PP) tests at 15 and 50 min, and Minnesota Rate of Manipulation (MRM) tests at 30 and 55 min. Subjects rated their thermal sensation and comfort just before the dexterity tests. T_f decreased ($p < 0.05$ for time × trial interaction) by 15 min of cold exposure during CON (33.6 ± 1.4–28.7 ± 2.0°C), but not during BAL (33.2 ± 1.4–30.6 ± 3.2°C); and after 30 min T_f remained warmer during BAL (23.3 ± 5.9°C) than CON (19.2 ± 3.5); however, by 50 min, T_f was no different between trials (14.1 ± 2.7°C). Performance on PP fell ($p < 0.05$) by 25% after 50 min in both trials; MRM performance was not altered by cold on either trial. Subjects felt colder ($p < 0.05$) and more uncomfortable ($p < 0.05$) during CON, compared to BAL. Thermal face protection was effective for maintaining warmer T_f and thermal comfort during cold exposure; however, local cooling of the hands during manual dexterity tests reduced this physiological advantage, and performance was not improved.

Keywords Reflex vasoconstriction · Heat loss · Thermal sensation

Introduction

While most people wear a hat during cold exposure, the face often remains exposed. Thermal face protection may be neglected for practical reasons, such as difficulty accommodating a balaclava under a helmet, or for personal reasons, such as not liking the appearance. Thermal face protection may also be overlooked because face skin temperature remains warmer during cold exposure than most other regions of the body (Boutcher et al. 1995; Webb 1992), and, while the face is sensitive to small changes in temperature (Stevens and Choo 1998), cooling the face results in less thermal discomfort compared to the same degree of cooling in other regions of the body (Nakamura et al. 2008). However, the higher facial skin temperature allows greater heat loss (Froese and Burton 1957), and facial cooling induces a reflex vasoconstriction that reduces blood flow to the fingers and toes (Brown et al. 2003; Heath and Downey 1990). Extremity cooling during cold-weather

Communicated by George Havenith.

The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. Human subjects participated in these studies after giving their free and informed voluntary consent. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

C. O'Brien (✉) · J. W. Castellani · M. N. Sawka
Thermal and Mountain Medicine Division,
U.S. Army Research Institute of Environmental Medicine,
Natick, MA 01760-5007, USA
e-mail: kate.obrien@us.army.mil

activity is an important concern in military, occupational and sports medicine communities for physical comfort (Adams and Smith 1962; Heus et al. 1995), manual dexterity (Enander 1987), and prevention of cold injury (Castellani et al. 2006). Interventions that blunt or delay the initial vasoconstrictor response in the extremities may be effective in maintaining warmer finger temperatures during cold exposure and deserve more attention. Whether extremity cooling can be limited by wearing thermal face protection during prolonged whole-body cold exposure is unknown.

Cold exposure of the face stimulates the trigeminal nerve, which activates a sympathetic pathway that induces vasoconstriction, as well as a parasympathetic pathway that induces bradycardia (Brick 1966; Heath and Downey 1990; Heistad et al. 1968; Hilz et al. 1999). Several studies have examined the impact of brief (up to 60 s) application of cold (0°C) compresses to the forehead and found reductions in finger and toe blood flow as high as 50–70% in subjects resting in a normal room temperature (Brown et al. 2003; Heath and Downey 1990; Hilz et al. 1999). In the only study with a longer cold exposure, Jennings et al. (1993) found a small (~0.6°C), but persistent decrease in finger skin temperature after 20 min of circulating cold water (10°C) through tubing on the cheeks of recumbent subjects during REM sleep. On blowing cold air (4°C, 18 m s^{-1}) on the face of subjects for 4 min, LeBlanc and Mercier (1992) found a 25% increase in circulating norepinephrine, indicating sympathetic activation, although they did not report the finger temperature. The results of these studies suggest that protecting the face from cold could delay or blunt reflex vasoconstriction in the extremities, and thereby also delay or blunt the finger cooling that occurs during cold exposure.

Over a prolonged cold exposure, heat loss from a bare face can also contribute to extremity cooling. Rapaport et al. (1949) reported that hands and feet will cool when whole-body heat loss exceeds heat production by 15%. Such a difference can easily occur with a bare face at low temperatures, because although the surface area of the face is small (~0.04 m^2), there is minimal vasoconstriction in this region, resulting in a high rate of heat loss. Froese and Burton (1957) provide an example of whole-body cold exposure (−4°C, 2.2 m s^{-1} wind) where about half of the resting heat production would be lost from a bare head if the rest of the body was well insulated (5 clo). They (Froese and Burton 1957) estimated that the addition of relatively little insulation (2.4 clo) on the head would restore heat balance, although a higher amount (3.5 clo) would be required if the face remained exposed to cold. If thermal face protection can restore heat balance, extremity cooling would also likely be limited.

To our knowledge, no one has investigated the effect of thermal face protection, compared to a bare face, on finger temperature during whole-body cold exposure over a prolonged period. This could be important for thermal comfort, manual dexterity, and risk of cold injury for people working in cold environments. Therefore, this study examined finger temperature during cold air exposure in subjects dressed in cold-weather clothing and their face was covered by a balaclava and goggles, and compared those responses to a condition where the face remained bare. We hypothesized that reflex vasoconstriction from facial cooling when the face was bare, in combination with greater heat loss from the exposed face, would reduce finger temperatures to a greater extent than when thermal face protection was worn. We also examined whether thermal face protection improved perception of thermal comfort, and whether the difference in finger temperature between conditions would be large enough to affect manual dexterity.

Methods

Ten healthy males participated in this study, which was approved by the appropriate scientific and human use review boards of the U.S. Army Research Institute of Environmental Medicine and U.S. Army Medical Research and Materiel Command. Each person volunteered after being informed of the purpose, experimental procedures, and known risks of the study. Investigators adhered to Army Regulation 70–25 and U.S. Army Medical Research and Materiel Command Regulation 70–25 on the use of volunteers in research. Participants were medically screened to exclude prior cold injury and any condition or medication that could interfere with body temperature regulation. The participants were 22 ± 3 years old, 177.6 ± 6.9 cm in height, had a body mass of 82.4 ± 17.9 kg, body surface area of 2.0 ± 0.2 m^2 (DuBois and DuBois 1916) and body fat, estimated from skinfold measurements (Durnin and Wormersly 1974), of 18.6 ± 3.6%.

Experiments were conducted at the same time of day, and subjects were familiarized with each experimental procedure. Each volunteer completed two cold air exposure trials, once while wearing a balaclava (0.8 clo on the face) and goggles to protect the face from direct cooling (BAL), and on another occasion with the balaclava pulled down off the face and no goggles to expose the face to cold wind (CON). The balaclava had a nylon mesh that covered the mouth. Volunteers were otherwise dressed in U.S. Army Extended Cold-Weather Clothing System (ECWCS, GEN 3) Polartec Power Dry grid fleece and loft parka and trousers for a total measured insulation value of 3.6 clo. They dressed in a 21°C room, donning parka, handwear, balaclava, and goggles just before entering the cold chamber to avoid overheating. Handwear consisted of insulated mitts worn over thin polyester gloves. Mitts were removed

during dexterity tasks, which were performed wearing only the thin gloves. The two trials were counterbalanced and spaced about a week apart. The temperature (−15°C) and wind speed (3 m s^{-1}) in the environmental chamber were equivalent to a wind chill temperature of −20°C (National Weather Service Windchill Chart). These conditions were selected to provide marked cooling to the face during CON with little risk of frostbite, such that the face protection during BAL might have the best conditions for reducing heat loss and minimizing extremity vasoconstriction.

Volunteers entered the cold chamber and stood facing the wind for 60 min. The wind was uniform across the front of their body, with the exception of a 30-cm high board at about waist level, which was attached to a table for the dexterity tests and protected the pieces from moving due to the wind. The timeline for cold exposure is shown on Fig. 1. After 15 min, volunteers removed their mitts to perform a Purdue Pegboard (PP) task that requires fine dexterity. The first part of the test involved placing as many pegs into holes as possible for 30 s with the right hand, left hand, and both hands. The second part of the test involved assembling a peg, washer, spacer, and another washer in each hole as many times as possible for 1 min. Data analysis for PP used the combined score of the average of peg placements (right hand, left hand, both hands) plus the score for assembly (counting each piece). They then put their mitts back on until 30 min, at which time they removed the mitts to perform a Minnesota Rate of Manipulation (MRM) task that requires gross hand dexterity. Data analysis for MRM used the combined score of the average of four times for placing blocks plus the time for turning blocks. They put their mitts back on once more until 50 min, at which time they completed the PP task immediately followed by the MRM task. Before the cold trials were conducted, volunteers had practiced both dexterity tests in temperate conditions while wearing the thin gloves five to six times until performance showed no further improvement over two sequential sessions. Volunteers were asked to rate their thermal sensation (TS) on a scale from 0.0 (unbearably cold) to 8.0 (unbearably hot) (Young et al. 1987) and thermal comfort (TC) on a scale from 1 (comfortable) to 4 (very uncomfortable) (Gagge et al. 1967) just before performing the dexterity tasks.

Heat flux transducers with integrated thermistors (Concept Engineering, Old Saybrook, CT) were attached at eight sites: cheek, hand, finger, foot, arm, chest, back, and calf. The core temperature (T_c) was measured with either a rectal thermistor (5 subjects) inserted 10 cm past the anal sphincter, or an esophageal thermistor (5 subjects) inserted to a depth of one-quarter of the subject's height, then adjusted 1–2 cm in either direction to locate the highest local temperature (both thermistors: Measurement Specialties, Inc., Hampton, VA). Subjects who were unable to place the esophageal thermistor used the rectal thermistor; the same thermistor was used for both trials. Core and skin temperature data and heat flux were recorded every 10 s. Mean weighted skin temperature (T_{sk}) and heat flux were calculated using a modified Hardy and Du Bois (1938) formula: $0.02 \times \text{cheek} + 0.4 \times \text{chest} + 0.14 \times \text{arm} + 0.05 \times \text{hand} + 0.19 \times \text{thigh} + 0.13 \times \text{calf} + 0.07 \times \text{foot}$. This formula was used because it included regions that experienced greater cooling (hand, foot, face). Cheek temperature was used instead of forehead temperature used in the original formula, and the weighting was reduced (from 0.07 to 0.02) to represent the smaller surface are of the face (~0.04 m^2) compared to the whole head. Since the temperature on the head was not measured, weighting for the chest was increased (from 0.35 to 0.40), as this site would have the least stimulus for vasoconstriction and the head also had little vasoconstrictor response to cold (Froese and Burton 1957). Mean body temperature (T_b) was calculated as $0.67 \times T_c + 0.33 \times T_{sk}$. A polar watch (Polar Electro Oy, Finland) was used to measure heart rate, which was recorded every 5 min.

Data were analyzed using a two-factor (trial × time) repeated measures ANOVA. For continuously measured variables, five time points (initial, 15, 30, 50, and 60 min) were analyzed for cheek, core, foot, and mean skin temperatures and for heart rate. For finger and hand temperatures, seven time points were analyzed, including the lowest values achieved during each of the dexterity tests, which occurred between 15 and 20; between 30 and 35, and between 50 and 60 min. Tukey's Honestly Significant Difference test was applied when significant main effects were found. Statistical significance was set at $p < 0.05$. Sample size estimation (Statistica, StatSoft, Inc.) based on an expected 2.3°C standard deviation in finger temperature after 60 min (Gonzalez et al. 1998) and a 2.5°C finger temperature difference at which significant differences in Purdue Pegboard scores have been observed with cooling

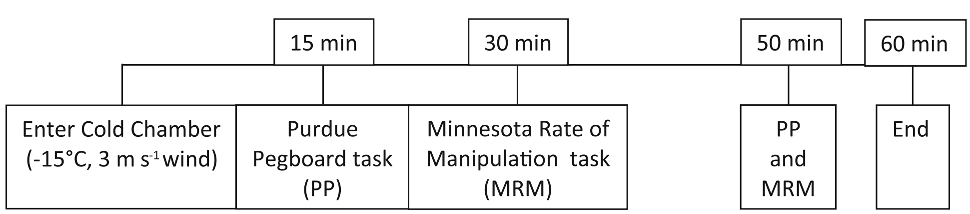

Fig. 1 Timeline of cold exposure and dexterity tasks

(Flouris et al. 2006) with power of 80% suggests that nine subjects would be required to detect a significant difference between BAL and CON. Data are expressed as mean ± standard deviation.

Results

Figure 2 shows T_c and T_{sk} during cold exposure for both trials. Initial T_c was similar between trials (both 37.0 ± 0.3°C) and did not change during BAL, but fell ($p = 0.001$ for time × trial interaction) during CON to 36.8 ± 0.4°C after 60 min. Esophageal temperature responds more quickly to changes in body temperature than rectal temperature (O'Brien et al. 1998), and in the five subjects using the esophageal thermometer the fall in core temperature was significant at 30 min, whereas for the five subjects using the rectal thermometer the change was significant at 60 min. Initial T_{sk} was similar between trials, but decreased faster ($p = 0.001$ for time × trial interaction) during CON (33.0 ± 0.5°C initially to 27.7 ± 0.6°C at 60 min) than BAL (33.1 ± 0.5–28.3 ± 0.7°C). Note that the calculation for T_{sk} included hand temperature, and at 60 min the mitts were off as subjects performed dexterity tests. Initial T_b was similar between trials, but decreased faster ($p < 0.001$ for time × trial interaction) with cold exposure during CON (35.7 ± 0.3°C initially to 33.8 ± 0.3°C at 60 min) than BAL (35.7 ± 0.2°C initially and 34.2 ± 0.2°C at 60 min). Heart rate (81 ± 9 b min^{-1}) did not differ between trials or over time.

Cheek temperature, shown in Fig. 3, was higher throughout cold exposure during BAL, compared to CON, and decreased over time on both trials ($p < 0.001$ for time × trial interaction). Finger, hand and foot temperatures are shown in Fig. 4. There was a significant time × trial interaction ($p = 0.012$) for finger temperature. After 15 min of cold air exposure, finger temperature was lower during CON, compared to the initial value, whereas finger temperature did not decrease during BAL. Thereafter, finger temperature decreased on both trials and each time point was significantly different from the next. Finger temperature was higher during BAL than CON at the time of the first dexterity test (PP) and at 30 min. Finger temperatures did not differ between trials at subsequent time points. There was a significant time × trial interaction ($p < 0.001$) for hand temperature. During BAL, hand temperature was not significantly different after 15 min, but thereafter each time point was significantly different from the next. During CON, hand temperature decreased initially and was significantly different from each time point to the next. Hand temperature was significantly higher during BAL than CON from the time of the second dexterity test (MRM). Hand temperatures were influenced by periodic removal of mitts

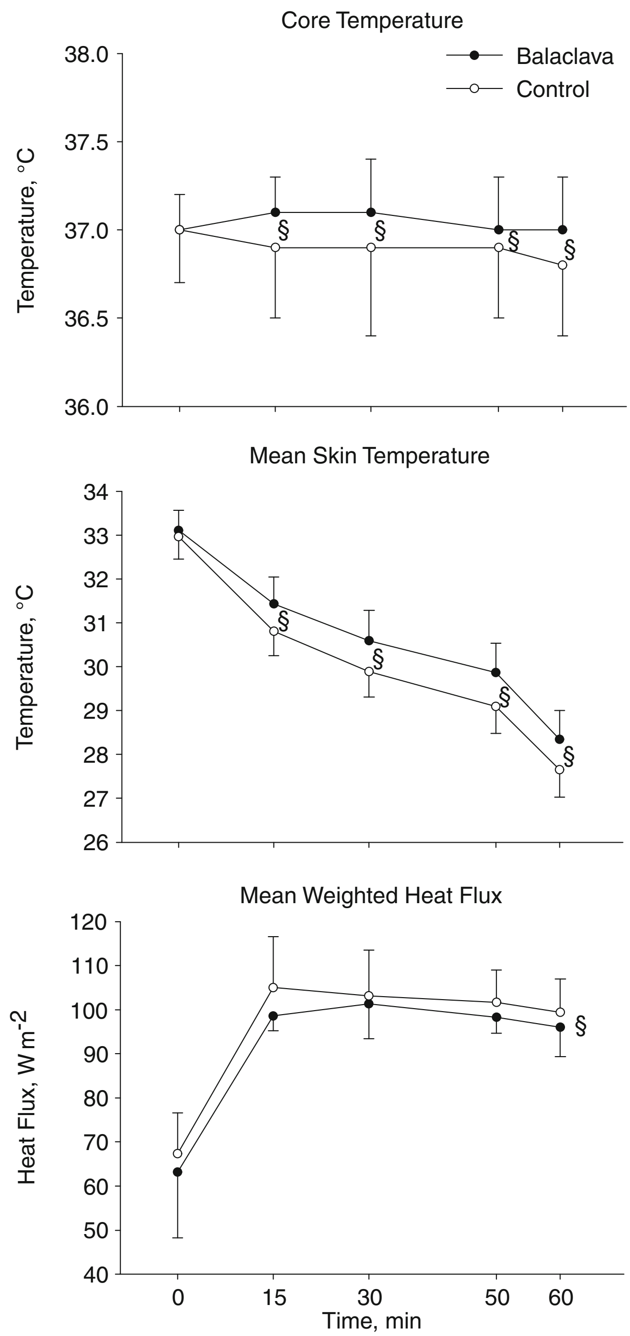

Fig. 2 Core and mean skin temperatures and mean weighted heat flux during cold exposure are presented for each trial. Values are mean ± SD. §Significant difference between trials

to perform dexterity tests, and finger temperature was additionally influenced by direct contact with cold metal and wood pieces of the dexterity tests. Foot temperature decreased ($p < 0.001$) similarly in both trials and was lower from each time point to the next.

Cheek heat flux, shown in Fig. 3, did not change over time during BAL (148.7 ± 63.8 W m^{-2} initially and 215.2 ± 40.0 W m^{-2} during cold exposure), but decreased

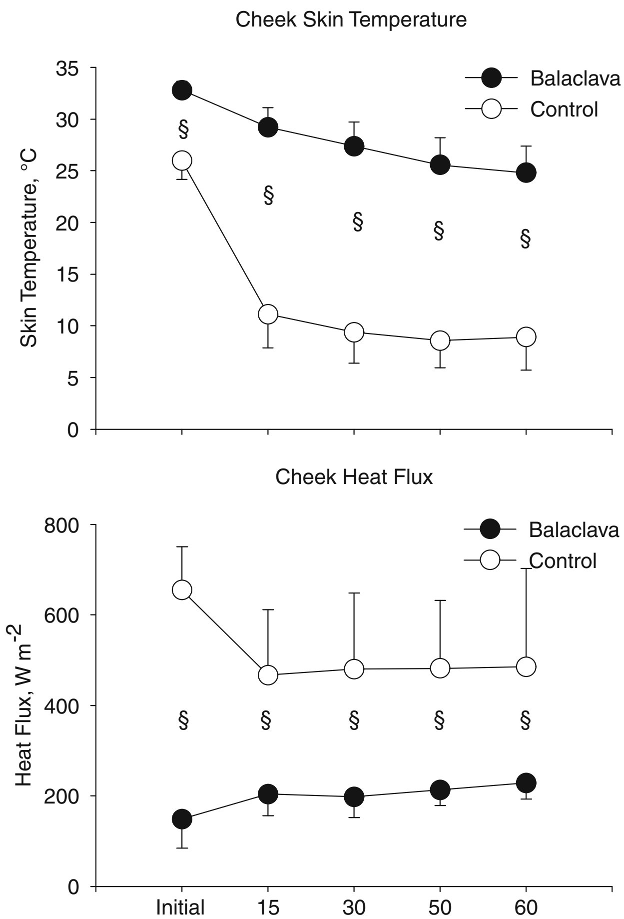

Fig. 3 Cheek temperature and heat flux during cold exposure are presented for each trial. Values are mean ± SD. §Significant difference between trials

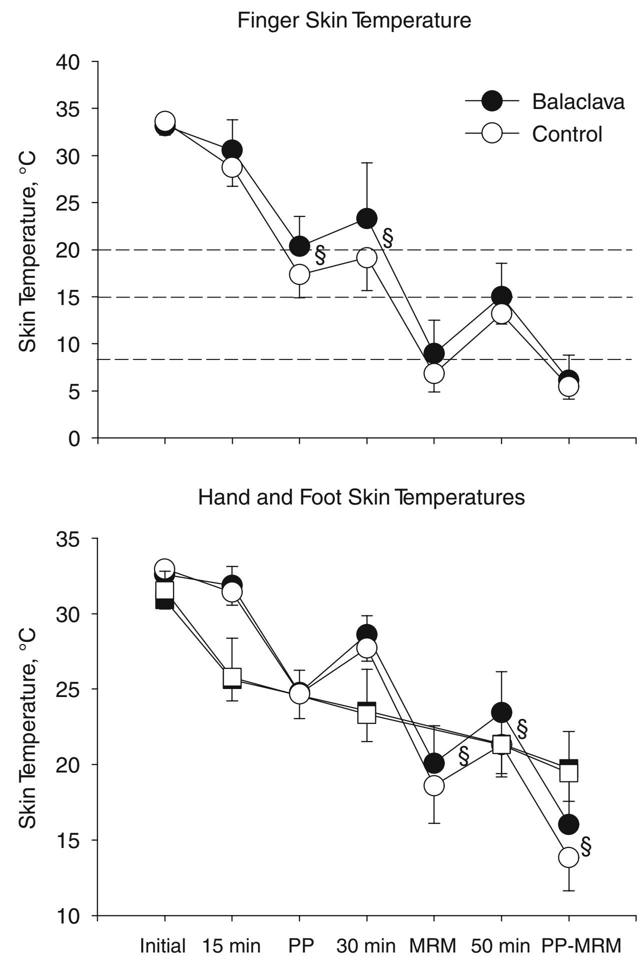

Fig. 4 Finger, hand (*circles*), and foot (*squares*) temperatures during cold exposure are presented for each trial. *PP* lowest finger temperature during the first (15 min) Purdue Pegboard test, which lasted 4–5 min; *MRM* lowest finger temperature during the first (30 min) Minnesota Rate of Manipulation test at 30 min, which lasted 7–8 min; *PP-MRM* lowest finger temperature during both tasks (at 50 min), which lasted 12–15 min. Foot temperatures are presented at 0, 15, 30, and 60 min. *Dashed lines* are drawn at the finger skin temperature associated with discomfort (20°C), impaired manual dexterity (15°C), and loss of tactile sensitivity (8°C). Values are mean ± SD. §Significant difference between trials

($p < 0.001$ for time × trial interaction) during CON and was higher at all time points (654.9 ± 96.5–478.3 ± 167.8 W m^{-2} during cold exposure), compared to BAL. Mean weighted heat flux, shown in Fig. 2, was higher overall during CON ($p = 0.032$ for trial main effect) than BAL, and increased ($p < 0.001$ for time main effect) during cold exposure after the initial value (CON 67.3 ± 9.2 W m^{-2} to an average of 102.0 ± 9.3 W m^{-2} during cold exposure; BAL 63.2 ± 14.9–98.5 ± 5.8 W m^{-2}). It should be noted that the gradient for heat flux is only directly from skin temperature to ambient air temperature for the face during CON; in all other regions, the presence of clothing reduces the gradient somewhat. Initial heat flux values are therefore relatively low, as the temperature inside the clothing has been warmed by body heat before entering the chamber; however, during cold exposure some of this heat escapes through the clothing and the air temperature near the skin is reduced, thereby increasing the gradient for heat flux. In the hands and fingers, this temperature was further reduced each time the mitts were removed to perform dexterity tests. At those times, heat flux increased dramatically without the insulation of the mitts, and the temperature of the mitts was lower when they were put back on after the dexterity tests, having lost heat that was previously contained by the insulation.

Table 1 shows dexterity, TS, and TC during cold exposure for each trial. Finger dexterity was degraded by 50 min of cold exposure, with lower ($p < 0.05$) scores on the PP task after 50 min (15 ± 3 units), compared to both baseline (the final practice with gloves at normal room temperature) (20 ± 3 units) and the performance after 15 min of cold exposure (18 ± 3 units), but there were no differences between trials. There was no statistically significant difference in performance on the MRM task due to cold exposure

Table 1 Purdue Pegboard and Minnesota Rate of Manipulation dexterity tests, and thermal sensation and thermal comfort ratings during cold exposure are presented for each trial

Trial	Baseline	15 min	30 min	50 min
Purdue Pegboard (pieces)				
CON	20 ± 3*	18 ± 3*	–	14 ± 2
BAL	20 ± 3*	18 ± 3*	–	15 ± 3
Minnesota Rate of Manipulation (s)				
CON	100 ± 11	–	109 ± 5	112 ± 18
BAL	100 ± 11	–	108 ± 12	113 ± 22
Thermal sensation (4 = comfortable)				
CON	–	3.0 ± 1.2*	2.4 ± 1.1*	1.9 ± 0.9
BAL[§]	–	3.4 ± 1.1*	2.8 ± 1.1*	2.4 ± 1.2
Thermal comfort (1 = comfortable)				
CON	–	2.0 ± 0.5*	2.4 ± 0.3*	2.7 ± 0.7
BAL[§]	–	1.6 ± 0.5*	1.8 ± 0.6*	2.0 ± 0.5

"Baseline" is the score from the last practice session at a normal room temperature while wearing gloves. Values are mean ± SD

* Significant difference from 50 min; [§] significant difference between trials

(100 ± 11 s during baseline; 108 ± 13 s at 30 min cold exposure; 113 ± 20 s at ~55 min cold exposure), nor was there any difference between trials. TS decreased with cold exposure (15 vs. 30 and 30 vs. 50 min; $p < 0.001$) and was lower ($p = 0.012$) during CON, indicating that subjects felt colder during CON, compared to BAL. TC increased with time (15 vs. 50 min, $p = 0.003$) and was higher ($p = 0.002$) during CON, indicating that subjects felt more uncomfortable during CON, compared to BAL.

Discussion

This study was the first to examine the potential benefit of thermal face protection on finger temperature, thermal comfort, and manual dexterity during prolonged cold air exposure. We hypothesized that limiting the degree of facial cooling during cold air exposure by wearing a balaclava and goggles would reduce the stimulus for extremity vasoconstriction, resulting in higher finger temperatures, compared to a bare face. The results support this hypothesis. During BAL, finger temperatures remained higher during the first 30 min and hand temperatures remained higher thereafter, compared to CON. In addition, the mean skin temperature remained warmer, core temperature was maintained, and subjects reported better thermal comfort and thermal sensation during BAL, compared to CON. While manual dexterity was not improved by face protection, this may have been confounded by the local cooling that occurred when mitts were removed to perform the dexterity tasks.

Reflex vasoconstriction has been shown to occur rapidly with facial cooling (Brown et al. 2003; Heath and Downey 1990; Heistad et al. 1968; Jennings et al. 1993) and was likely an important early mechanism for finger cooling during CON, where cheek temperature fell abruptly upon cold exposure and finger temperature fell by 4.9°C in the first 15 min. Thermal face protection during BAL attenuated this reflex vasoconstriction, resulting in a slower initial rate of finger cooling on that trial. Reflex vasoconstriction also occurs with whole-body cooling, beginning as mean skin temperature falls from thermoneutral. The greater initial fall in both mean skin and core temperatures during CON likely also contributed to more rapid finger cooling on that trial. Finally, local cooling was a factor during both trials as mitts were periodically removed to perform dexterity tests.

Reflex vasoconstriction primarily regulates blood flow to cutaneous blood vessels and to arteriovenous anastomoses, which are important in the regulation of blood flow in the fingers (Hales and Iriki 1977; Roberts et al. 2002). Local cooling may modulate the contractile response in the capillaries through adrenergic mechanisms, including altering the response of vascular smooth muscle to norepinephrine (NE), altering release, reuptake or breakdown of NE, altering the affinity of α2-adrenoceptors for NE, or inducing translocation of receptors to cell membranes; through non-adrenergic mechanisms, such as inhibition of the nitric oxide system; and through a direct effect of cold on blood vessels (Alvarez et al. 2006; Chotani et al. 2000; Flavahan et al. 1985; Jeyaraj et al. 2001; Shepherd et al. 1983; Wenger et al. 1985). While reflex and local cooling vasoconstrictor responses are not entirely additive, each can contribute to the overall degree of vasoconstriction, and the magnitude of each effect is related to the degree of cooling in that region (Alvarez et al. 2006). The addition of local cooling may explain the lack of difference in finger temperatures between trials at the end of the 60-min exposure, even though finger temperature was higher for the first half of the cold exposure during BAL.

The higher finger temperature during BAL was not associated with improved manual dexterity, compared to CON. Manual performance degrades if cooling is sufficient to reduce not only skin surface temperature, but also underlying tissue temperatures; therefore, a longer duration of cooling has a greater effect on reducing performance (Clark and Cohen 1960). Reduced strength as muscle temperature falls below ~28°C (Bergh and Ekblom 1979), decreased joint mobility as synovial fluid viscosity increases below ~27°C (Hunter et al. 1952), slower nerve conduction velocity at nerve temperatures below ~20°C (de Jong et al. 1966), and reduced tactile sensation at skin temperature below ~8°C (Provins and Morton 1960) can all contribute to reductions in performance. Finger dexterity degrades sharply below a finger temperature of 15°C, most likely due

to reductions in nerve conduction velocity and joint mobility (Enander 1987; Heus et al. 1995). In the present experiment, finger temperature was well above this level for the first PP test, and no performance degradation occurred on either trial. At the time of the second PP test, the finger temperature was well below 15°C on both trials, and performance was similarly degraded on both.

Hand temperature was above 20°C when subjects began the last dexterity tests (PP, followed by MRM). By the end of the MRM test, the hand temperature remained above 15°C during BAL (16.0 ± 3.1°C), but had fallen below that threshold during CON (13.8 ± 2.2°C); however, there was no degradation in MRM performance on either trial, and no difference between trials. Since this temperature was only reached at the end of the MRM test, the duration of cooling may not have been long enough to impair performance during CON. In addition, the sensor was placed on the dorsal hand, not over a hand muscle; therefore, hand muscle temperature may not have fallen below the level at which performance degradation would occur. Hand dexterity on the MRM tests is more likely to be influenced by reduced muscle temperature, since it does not require the same fine motor control as the PP test.

The periodic removal of mitts to perform dexterity tasks, in combination with the conductive cooling of the fingers as they handled the pegs and blocks, likely allowed the direct effect of local cooling to ultimately eliminate the advantage of the balaclava for blunting the fall in finger temperature that was evident after 30 min, whereas hand temperature was higher during BAL for the remainder of the cold exposure. While finger temperature decreased during both trials, it was initially at a slower rate during BAL (0.17°C min^{-1}), compared to CON (0.33°C min^{-1}). If subjects had not experienced additional local cooling when they removed their mitts to perform dexterity tasks, such rates of cooling may have persisted, resulting in warmer finger temperatures during BAL throughout cold exposure.

While wearing face protection during cold exposure resulted in higher hand and finger temperatures, foot temperature did not differ between trials. Several factors could contribute to this, including the dependent position of the feet in standing subjects, lower sensitivity to reflex control of blood flow compared to the hand, and conductive heat loss to the floor. Dependent position of a limb results in increased local pressure, vasoconstriction, and lower skin temperature (Hassan and Tooke 1988a; Youmans et al. 1935). These changes are primarily due to the venoarteriolar reflex, a myogenic response that may be mediated by local nonadrenergic neurogenic mechanisms (Crandall et al. 2002; Hassan and Tooke 1988b). While a dependent position could explain why foot temperature was lower than that of the hand, it was not clear why foot temperature was not affected by thermal face protection. In supine subjects, Heath and Downey (1990) reported reductions in both toe and finger blood flow upon application of a cold compress to the forehead, but the reduction in toe blood flow was ~20% less than that in the finger. This suggests that the foot may be less responsive to reflex vasoconstriction than the hand. Bader and Macht (1948) found that when seated subjects were in a cool (15°C) room, warming the face (to 42–44°C) increased hand skin temperature and blood flow, but toe temperatures were only minimally affected, suggesting that the toe may also be less responsive to reflex warming. However, when they repeated the experiment at a room temperature of 23.5°C, both hand and toe temperatures increased upon warming the face (Bader and Macht 1948). Thus, the cold environment appeared to blunt the increase in blood flow due to reflex warming in the feet, but not in the hands. Likewise, in our subjects, either whole-body or local cooling may have a stronger influence on the feet, making those vessels less responsive to reflex changes. Foot temperature initially fell faster than hand temperature, which could reflect greater sensitivity to cold of the blood vessels in the feet and/or influence of conductive heat loss to the floor due to insufficient boot insulation.

Besides the effects of reflex and local cooling, facial cooling during CON also likely increased the metabolic rate (Stroud 1991). Stroud (1991) found an increase in resting metabolic rate of ~11.6 W when cold (−20°C) air was blown on the face of seated subjects. A similar increase in heat production in the present study would likely have prevented the fall in core temperature during CON; therefore, metabolic rate either did not increase to that extent, and/or other avenues of heat loss were important during CON. One important source is respiratory convective and evaporative heat losses, which can be 11% (Brebbia et al. 1957) to 25% (Cain et al. 1990) of resting metabolic rate at ambient temperatures of −20°C. Respiratory heat losses can be limited by simply covering the mouth and nose with a scarf, surgical mask, or screen (Cain et al. 1990; Rosen and Rosen 1995), such as the nylon mesh that covered the mouth during BAL. Thus, while metabolic rate may have been higher during CON, respiratory heat loss was also likely higher on that trial, whereas it was likely somewhat conserved during BAL. Clearly, any increase in heat production during CON was not sufficient to offset the higher heat loss from the exposed face. Total mean weighted heat flux was 7.6 W higher during CON than BAL, whereas for the face alone heat flux was 10.5 W higher during CON. This indicates that heat flux over the rest of the body was actually lower during CON, yet core temperature still fell slightly (0.2°C) during the trial. Unfortunately, no measurements of metabolic rate or respiratory heat losses were made in the present investigation.

To distinguish the effects of reflex vasoconstriction from a negative heat balance and from direct effects of local

cooling, it would be necessary to prevent whole-body cooling (by increasing clothing insulation) and local cooling (by not remove mitts during the experiment), and include a trial with equivalent heat loss as from the face, but in a region that does not elicit reflex vasoconstriction. For example, Brown et al. (2003) included a "sham" condition where the cold stimulus was applied to the top of the head. The top of the head has minimal vasoconstriction, thus heat loss would occur without the reflex vasoconstriction that would occur with facial cooling. While Brown et al. (Brown et al. 2003) did not report finger blood flow during the sham condition, no reflex changes in heart rate or mean arterial pressure occurred, suggesting that this was a suitable control condition.

This study demonstrates that thermal face protection during cold exposure provides a physiological advantage by allowing warmer finger, and mean skin and core temperatures and improved thermal comfort, compared to a bare face during 60 min cold (−15°C) air exposure with 3 m s^{-1} wind. This did not translate into better sustained manual dexterity, because removing mitts to perform dexterity tasks allowed local cooling to reduce finger temperature below levels associated with performance degradation. In situations where frequent removal of mitts is not required, it is likely that warmer finger temperatures would be sustained for a longer period of time. If this is effective under colder conditions, thermal face protection could offer some protection against cold injury to the extremities. Thermal face protection would also likely be advantageous when sleeping in the cold, where increased thermal comfort could improve sleep quality. Rapaport et al. (1949) reported that extremity cooling occurs when heat loss exceeds heat production by ~12–15 W. If clothing insulation over the rest of the body were sufficient to limit heat loss, this suggests that thermal face protection would become important for maintaining extremity temperatures at ambient temperatures below −5 to −10°C, where heat loss from the face would be 13–14 W (Froese and Burton 1957). If whole-body insulation is inadequate, thermal face protection becomes more important for limiting body heat loss.

Acknowledgments We are sincerely grateful to the volunteers who participated in this study. Many thanks are also due to Mr. Lenny Elliott, Mr. Thomas Endrusick, and Mr. Vincent Forte, Jr., for their technical expertise and assistance.

Conflict of interest The authors declare that they have no conflict of interest.

References

Adams T, Smith RE (1962) Effect of chronic local cold exposure on finger temperature responses. J Appl Physiol 17:317–322

Alvarez GE, Zhao K, Kosiba WA, Johnson JM (2006) Relative roles of local and reflex components in cutaneous vasoconstriction during skin cooling in humans. J Appl Physiol 100:2083–2088

Bader ME, Macht MB (1948) Indirect peripheral vasodilatation produced by the warming of various body areas. J Appl Physiol 1:215–226

Bergh U, Ekblom B (1979) Physical performance and peak aerobic power at different body temperatures. J Appl Physiol 46:885–889

Boutcher SH, Maw GJ, Taylor NAS (1995) Forehead skin temperature and thermal sensation during exercise in cool and thermoneutral environments. Aviat Space Environ Med 66:1058–1062

Brebbia DR, Goldman RF, Buskirk ER (1957) Water vapor loss from the respiratory tract during outdoor exercise in the cold. J Appl Physiol 11:219–222

Brick I (1966) Circulatory responses to immersing the face in water. J Appl Physiol 21:33–36

Brown CM, Sanya EO, Hilz MJ (2003) Effect of cold face stimulation on cerebral blood flow in humans. Brain Res Bull 61:81–86

Cain JB, Livingstone SD, Nolan RW, Keefe AA (1990) Respiratory heat loss during work at various ambient temperatures. Respir Physiol 79:145–150

Castellani JW, Young AJ, Ducharme MB, Giesbrecht GG, Glickman EL, Sallis RE (2006) Prevention of cold injuries during exercise. Med Sci Sports Exerc 38:2012–2029

Chotani MA, Flavahan S, Mitra S, Daunt D, Flavahan NA (2000) Silent α2C-adrenergic receptors enable cold-induced vasoconstriction in cutaneous arteries. Am J Physiol 278:H1075–H1083

Clark RE, Cohen A (1960) Manual performance as a function of rate of change in hand skin temperature. J Appl Physiol 15:496–498

Crandall CG, Shibasaki M, Yen TC (2002) Evidence that the human cutaneous venoarteriolar response is not mediated by adrenergic mechanisms. J Physiol 538:599–605

de Jong RH, Hershey WN, Wagman IH (1966) Nerve conduction velocity during hypothermia in man. Anesthesiology 27:805–810

DuBois D, DuBois EF (1916) Clinical calorimetry: a formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871

Durnin JVGA, Wormersly J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged 16 to 72 years. Br J Nutr 32:77–97

Enander A (1987) Effects of moderate cold on performance of psychomotor and cognitive tasks. Ergonomics 30:1431–1445

Flavahan NA, Lindblad LE, Verbeuren TJ, Shepherd JT, Vanhoutte PM (1985) Cooling and α_1- and α_2-adrenergic responses in cutaneous veins: role of receptor reserve. Am J Physiol 249:H950–H955

Flouris AD, Cheung SS, Fowles JR, Kruisselbrink LD, Westwood DA, Cariillo AE, Murphy RJL (2006) Influence of body heat content on hand function during prolonged cold exposures. J Appl Physiol 101:802–808

Froese G, Burton AC (1957) Heat losses from the human head. J Appl Physiol 10:235–241

Gagge AP, Stolwijk JAJ, Hardy JD (1967) Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1:1–20

Gonzalez RR, Endrusick TL, Santee WR (1998) Thermoregulatory responses to cold: effects of handwear with multi-layered clothing. Aviat Space Environ Med 69:1076–1082

Hales JRS, Iriki M (1977) Differential thermal influences on skin blood flow through capillaries and arteriovenous anastomoses, and on sympathetic activity. Bibliotheca Anatomica 16:189–191

Hardy JD, Du Bois EF (1938) The technic of measuring radiation and convection. J Nutr 15:461–475

Hassan AAK, Tooke JE (1988a) Effect of changes in local skin temperature on postural vasoconstriction in man. Clin Sci 74:201–206

Hassan AAK, Tooke JE (1988b) Mechanism of the postural vasoconstrictor response in the human foot. Clin Sci 75:379–387

Heath ME, Downey JA (1990) The cold face test (diving reflex) in clinical autonomic assessment: methodological considerations and repeatability of responses. Clin Sci 78:139–147

Heistad DD, Abboud FM, Eckstein JW (1968) Vasoconstrictor response to simulated diving in man. J Appl Physiol 25:542–549

Heus R, Daanen HAM, Havenith G (1995) Physiological criteria for functioning of hands in the cold. Appl Ergonomics 26:5–13

Hilz MJ, Stemper B, Sauer P, Haertl U, Singer W, Axelrod FB (1999) Cold face test demonstrates parasympathetic cardiac dysfunction in familial dysautonomia. Am J Physiol 276:R1833–R1839

Hunter J, Kerr EH, Whillans MG (1952) The relation between joint stiffness upon exposure to cold and the characteristics of synovial fluid. Can J Med Sci 30:367–377

Jennings JR, Reynolds CF, Bryant DS, Berman SR, Buysse DJ, Dahl RE, Hoch CC, Monk TH (1993) Peripheral thermal responsivity to facial cooling during sleep. Psychophysiology 30:374–382

Jeyaraj SC, Chotani MA, Mitra S, Gregg HE, Flavahan NA, Morrison KJ (2001) Cooling evokes redistribution of α2C-adrenoceptors from Golgi to plasma membrane in transfected human embryonic kidney 293 cells. Mol Pharmacol 30:1195–1200

LeBlanc J, Mercier I (1992) Cold wind stimulation reflex. J Appl Physiol 73:1704–1707

Nakamura M, Yoda T, Crawshaw LI, Yasuhara S, Saito Y, Kasuga M, Nagashima K, Kanosue K (2008) Regional differences in temperature sensation and thermal comfort in humans. J Appl Physiol 105:1897–1906

O'Brien C, Hoyt RW, Buller MJ, Castellani JW, Young AJ (1998) Telemetry pill measurement of core temperature during active heating and cooling. Med Sci Sports Exerc 30:468–472

Provins KA, Morton R (1960) Tactile discrimination and skin temperature. J Appl Physiol 15:155–160

Rapaport SI, Fetcher ES, Shaub HG, Hall JF (1949) Control of blood flow to the extremities at low ambient temperatures. J Appl Physiol 2:61–71

Roberts M, Rivers T, Oliveria S, Texeira P (2002) Adrenoceptor and local modulator control of cutaneous blood flow in thermal stress. Comp Physiol Biochem 313:485–496

Rosen AE, Rosen JM (1995) Effect of a face mask on respiratory water loss during sleep in cold conditions. Wilderness Environ Med 6:189–195

Shepherd JT, Rusch NJ, Vanhoutte PM (1983) Effect of cold on the blood vessel wall. Gen Pharmacol 14:61–64

Stevens JC, Choo KK (1998) Temperature sensitivity of the body surface over the life span. Somatosens Mot Res 15:13–28

Stroud MA (1991) Effects on energy expenditure of facial cooling during exercise. Eur J Appl Physiol 63:376–380

Webb P (1992) Temperatures of skin, subcutaneous tissue, muscle and core in resting men in cold, comfortable and hot conditions. Eur J Appl Physiol 64:471–476

Wenger CB, Bailey RB, Roberts MF, Nadel ER (1985) Interaction of local and reflex thermal effects in control of forearm blood flow. J Appl Physiol 58:251–257

Youmans JB, Akeroyd JH, Frank H (1935) Changes in the blood and circulation with changes in posture. The effect of exercise and vasodilatation. J Clin Invest 14:739–753

Young AJ, Sawka MN, Epstein Y, Decristofano B, Pandolf KB (1987) Cooling different body surfaces during upper and lower body exercise. J Appl Physiol 63:1218–1223